Thermal mineralized waters and active neotectonics in the Mérida terrace, Venezuela: hydrogeochemical and isotopic evidence.

Aguas termomineralizadas y neotectónica activa en la meseta de Mérida, Venezuela: evidencias hidrogeoquímicas e isotópicas.

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Abstract

This research evaluates the origin and relationship with neotectonics of the thermomineral waters at the base of the Mérida terrace, Venezuela, by integrating hydrogeochemical, isotopic, and geophysical methods. The main objective was to determine whether these waters, together with La Rosa lagoon, constitute evidence of active faulting associated with the Boconó Fault System. The methodology included in-situ analysis of physicochemical parameters, measurement of stable isotopes (δ^2H and $\delta^{18}O$) in 14 water samples to trace their origin, the execution of vertical electrical soundings (VES) to identify water tables, and a bathymetric and sedimentological study of the lagoon. The results indicate that all waters are of meteoric origin, with emergence temperatures ranging between 27 °C and 43.5 °C, confirming their thermal nature. Two geochemical affinities were established based on isotopic composition, linking recharge areas (Albarregas River, streams, and La Rosa lagoon itself) with thermal discharge points. The VES revealed shallow and deep water tables that facilitate fluid circulation. Bathymetry of La Rosa lagoon showed a maximum depth of 3.55 m in its northwestern sector, with evidence of active subsidence which, together with its elongated triangular morphology and the presence of microfractures in the sediments, confirms it as a fault sag pond. In conclusion, the hydrothermal system is directly controlled by the neotectonic activity of the Boconó Fault, which acts as a conduit for deep water circulation and generates surface deformation, demonstrating the usefulness of these techniques for mapping active faults.

Keywords: thermal waters, stable isotopes, neotectonics, Boconó Fault, hydrogeochemistry, Mérida terrace.

Resumen

Esta investigación evalúa el origen y la relación con la neotectónica de las aguas termomineralizadas en la base de la meseta de Mérida, Venezuela, integrando métodos hidrogeoquímicos, isotópicos y geofísicos. El objetivo principal fue determinar si estas aguas, junto con la laguna La Rosa, son evidencia de fallamiento activo asociado al Sistema de Falla de Boconó. La metodología incluyó el análisis in situ de parámetros fisicoquímicos, la medición de isótopos estables (δ^2H y $\delta^{18}O$) en 14 muestras de agua para trazar su origen, la realización de sondeos eléctricos verticales (SEV) para identificar niveles freáticos y un estudio batimétrico y sedimentológico de la laguna. Los resultados indican que todas las aguas son de origen meteórico, con temperaturas de surgencia entre 27 °C y 43,5 °C, lo que confirma su carácter termal. Se establecieron dos afinidades geoquímicas basadas en la composición isotópica, vinculando áreas de recarga (río Albarregas, quebradas y la propia laguna La Rosa) con los puntos de descarga termal. Los SEV revelaron niveles freáticos someros y profundos que facilitan la circulación de fluidos. La batimetría de la laguna La Rosa mostró una profundidad máxima de 3,55 m en su sector noroeste, con evidencia de subsidencia activa que, junto con su morfología triangular alargada y la presencia de microfracturas en los sedimentos, la confirman como una ciénaga de falla. En conclusión, el sistema hidrotermal está directamente controlado por la actividad neotectónica de la Falla de Boconó, que actúa como conducto para la circulación de aguas profundas y genera deformación en superficie, demostrando la utilidad de estas técnicas para la cartografía de fallas activas.

Palabras clave: aguas termominerales, isótopos estables, neotectónica, Falla de Boconó, hidrogeoquímica, meseta de Mérida

1 Introduction

The Mérida terrace, located in western Venezuela, is traversed by the Boconó Fault System, one of the most important tectonic structures in the country, widely studied for its seismic activity and influence on regional geomorphology (Alvarado et al., 2021; Schubert & Vivas, 1993). At the base of the natural slope of the terrace, several thermomineralized water springs are found, whose origin and relationship with active tectonics had not yet been studied in detail.

Thermomineralized waters result from the infiltration of meteoric water that circulates at depth, increasing its temperature due to the geothermal gradient and emerging through permeable structures such as faults or fractures (Pinagua, 1992). Their chemical composition is defined by interaction with the geological materials traversed and is usually associated with areas of active tectonics and physicochemical characteristics (salt content, temperature, conductivity, etc.) that can be highly variable and frequently associated with zones of active tectonics (Burguera et al., 1980). These waters can be classified according to their geological origin, predominant chemical composition, and temperature range, allowing distinction between telluric and magmatic systems, different hydrochemical types (for example, chlorinated, sulfated, bicarbonated, or sulfurous), and thermal categories from cold to hyperthermal (Castany, 1971; Clark & Fritz, 1997; Hidromed, 2025).

From a structural point of view, neotectonics studies recent tectonic processes, including active tectonics, responsible for the generation of faults that have experienced movements in the Quaternary and retain reactivation potential (Wallace, 1986; Winslow, 1986). Geomorphological features associated with active faults include linear valleys, scarps, sag ponds, thermal springs, and landslides (Audemard et al., 2007). The Boconó Fault System, a dextral strike-slip structure approximately 500 km in length, crosses the Venezuelan Andes with active segments in the Mérida terrace, including La Rosa Fault, which is located in the study area (Alvarado et al., 2021).

In this context, the present work aims to determine the origin of the thermomineralized waters located at the foot of the Mérida terrace slope, their geochemical evolution, and their relationship with active neotectonics, through the integrated analysis of hydrogeochemical parameters, stable water isotopes, vertical electrical soundings, and the morphometric study of La Rosa lagoon.

2 Geological Context

The Mérida Cordillera is one of the most prominent geological and morphological units in western Venezuela; it extends approximately 350 km in a southwest-northeast direction, with a maximum width of nearly 100 km, and is formed by mountain chains associated with reverse, normal, and strike-slip faults controlled by the Boconó Fault System, which accommodates the interaction between the Maracaibo block and the South American plate (Audemard, 2003; Taboada et al., 2000). The basement, of Precambrian–Paleozoic age, includes the Caparo Block, composed of ancient metamorphic rocks covered by Ordovician–Silurian sediments (La Marca, 1997), upon which a complex tectonic evolution is superimposed, encompassing the Hercynian Orogeny and Mesozoic extensional episodes linked to the rifting of the northern margin of South America (Castrillo, 1998).

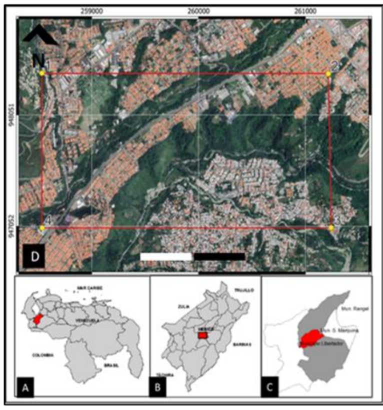
During the Quaternary, the region was affected by the Mérida glaciation, documented for the late Upper Pleistocene and early Holocene (Schubert, 1976), and the current Mérida terrace functioned as a floodplain filled with fluvial sediments from the Chama, Mucujún, and Albarregas rivers, subsequently incised by fluvial downcutting and tectonic uplift. The Boconó Fault, with NE strike and dextral transcurrent character, divides the cordillera into the Sierra Norte and Sierra Nevada blocks and, together with the Serranía del Escorial, controls the diversion of the Albarregas River and the compartmentalization of the terrace where the city of Mérida is located, characterized by gentle slopes (<5°) on the terraced surface and deeply incised valleys, especially that of the Chama River (Cabello, 1966; Nava, 2009). The local structural geology is dominated by the Boconó–Morón–El Pilar segment of the Venezuelan Fault System, with N45°E strike, 1–5 km width, and length of approximately 500 km (Dávila & Pacheco, 2009), along with active faults in the Mérida terrace, such as Albarregas, La Hechicera, Mucujún, and Jají, which juxtapose Paleozoic, Mesozoic, and Tertiary units and generate intense fracturing, a condition that controls both the geomorphology and the presence of La Rosa lagoon and the associated thermal springs (Google, 2022).

3 Methodology

The area is located within the metropolitan area of the city of Mérida, Venezuela, defined through a polygon of approximately 3.5 km² that encompasses the El Carrizal, Las Tapias, and El Chama sectors, summarized in Figure 1.

For its configuration, an analysis of recent aerial photographs and satellite images was conducted (Google, 2022), along with the UTM coordinates of known thermal springs. This was supported by an exhaustive and systematic state-of-the-art investigation, which included the compilation of undergraduate theses, scientific articles, maps, and institutional reports from FUNVISIS, INGEOMIN, and ULA related to the neotectonics of the Boconó Fault, the thermal springs of Mérida State, and the geomorphology of the Mérida terrace. Complementarily, photogeological reconnaissance allowed the identification of straight lineaments, triangular scarps, aligned valleys, and elongated depressions, which are indicative evidence of active fault structures.

Fieldwork was structured in four parallel and key research lines, described as follows:



Punto	Este (m) UTM	Norte (m) UTM
1	258533	948428
2	258533	948425
3	258533	947032
4	258547	947032

Figure 1. Location of the study area. A: national. B: regional. C: local. D: study area polygon.

Line 1. Photogeological Analysis and Field Reconnaissance. During the fieldwork, a structural geological mapping was carried out at a scale of 1:5,000, with systematic recording of strikes and dips of the main discontinuities (fractures, fault planes, and stratification). Additionally, an in situ photogeological analysis was conducted, allowing the correlation of field observations with the main structures recognized in aerial images. Measurements and observations were performed using a geological compass, metric scales, measuring tape, and photographic camera for the recording and documentation of structures. In this context, and with the support of local residents, it was possible to identify more thermal water points than initially planned. A total of four main thermal manifestations were studied, distributed in two zones: three of them located in the El Chama sector and one in the El Chamita sector. At each study point, at least two thermal sub-springs were identified, located very close to each other, forming small groups of closely spatially associated emergences (Figure 2).

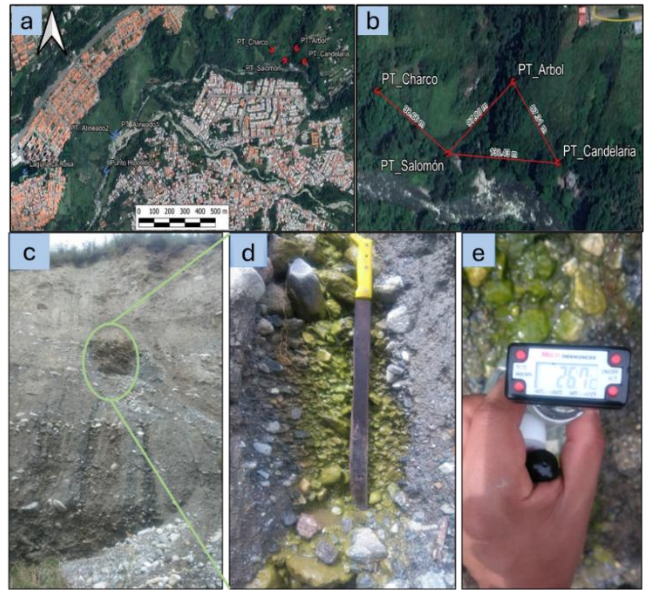


Figure 2. A "aligned" thermal spring is presented: the satellite image (a) shows the thermal springs located in the El Galerón sector (El Chamita), while in the close-up (b) the El Chama springs are detailed with their respective distances. In (c), the main scarp of the landslide through which the waters emerge is observed, and in (d) the characteristic green/yellow trail of the microbial mat, formed by thermophilic bacterial pigments. Finally, in (e) the temperature recorded in the hypothermal spring is specified.

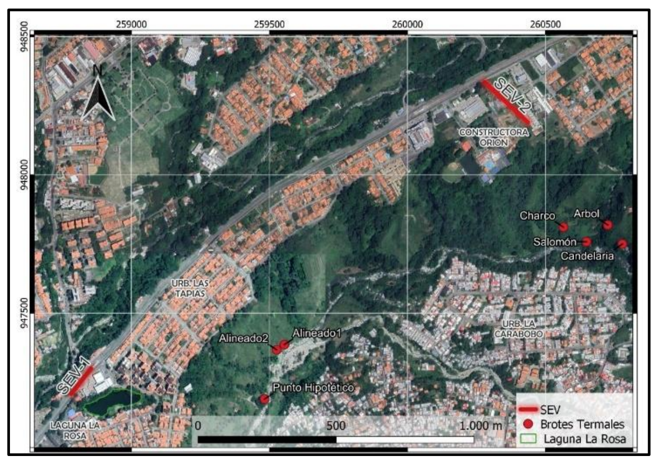


Figure 3. Location of the electrical line arrays in the execution of the vertical electrical soundings.

Line 2. Geophysical Characterization. With the purpose of identifying phreatic levels and characterizing the shallow stratigraphy, two vertical electrical soundings (VES) were carried out (Figure 3), using the Schlumberger array, with a maximum electrode separation AB/2 of 100 m. The measurements were performed using a 270 DAGAN resistivity meter, copper electrodes, and measuring tape for distance control.

The results obtained are presented in Figure 4, where the resistivity variations associated with the different subsurface geological units are observed.

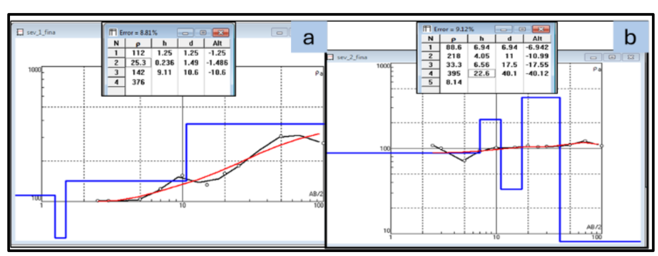


Figure 4. Resistivity variations associated with the different geological units encountered. a. VES-1. b. VES-2

Line 3. Bathymetric Survey and Sediment Sampling. To characterize the internal morphometry and sedimentary structure of La Rosa lagoon, a bathymetric survey was conducted complemented with sediment core extraction. For bathymetry, a metal raft with barrels at its base was used, which ensured buoyancy during measurement transects (Figure 5a). The survey was performed using the sounding method, appropriate for shallow water bodies, consisting of determining the depth from the vertical distance between the water surface and the lagoon bed. Previously, a navigation grid and a lagoon perimeter line were defined from a vector data model generated in a geographic information system (GIS), upon which several transverse profiles and one longitudinal profile were traced (Figure 5b). In the field, the planimetric position (X, Y) of each measurement point was recorded using a GPS receiver, while the depth elevation (Z) was obtained by lowering a plumb line until contact with the bottom at each station, covering both internal transects and the perimeter of the water body. Positioning was carried out with a global positioning system (GPS) based on the NAVSTAR constellation, which allowed continuous coverage for two-dimensional navigation and georeferencing of sounding points with a 10 m grid.

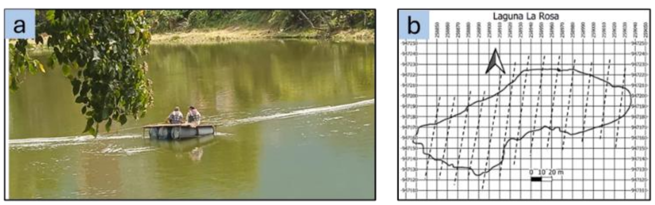
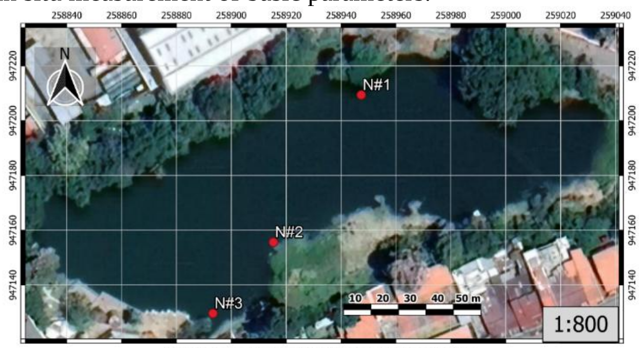


Figure 5. a. Image of the metal raft with barrels at its base. b. Sketch of longitudinal and transverse navigation lines, georeferenced with a grid every 10 meters.

The altimetric determination was carried out using a sounding lead consisting of a truncated conical weight suspended from a marked and calibrated sounding line, a technique suitable for water bodies with little wave action such as La Rosa lagoon and in accordance with the objectives of this study.

Complementarily, three sediment cores were extracted (Figure 6), using 3-inch diameter PVC pipes, reaching maximum depths of 1.6 m. Each core was described in detail in terms of lithology, color, texture, and sedimentary structures, using a PVC corer, a 10 kg mallet, spatula, and photographic camera, which allowed preserving the integrity of the material and documenting its characteristics in situ.

Line 4. Isotopic Analysis. With the purpose of establishing the origin of the water and its hydrogeochemical evolution, stable isotopes $\delta^{18}O$ and $\delta^{2}H$ were analyzed in 14 water samples (thermomineral waters, surface waters from the Albarregas River, streams, La Rosa lagoon, runoff, and municipal network). The samples were collected with a 24-hour interval post-rainfall in order to avoid the direct influence of recent precipitation on the isotopic composition, using 15 mL PE bottles rinsed X3, sealed with parafilm to prevent evaporation. The analysis was performed at the Water and Soils Laboratory of the Inter-American Center for Environmental and Territorial Development Research (CIDIAT-ULA); using a DLT-100 laser spectrometer (cavity ring-down spectroscopy), precision ±0.3‰ ($\delta^{18}O$) and ±2‰ ($\delta^{2}H$) vs VSMOW. Along with these samples, five of them were additionally destined for physicochemical characterization (temperature, pH, electrical conductivity, and major ions), using a WTW multiparametric probe for the in situ measurement of basic parameters.



ID	Nombre	Norte UTM	Este UTM	Longitud	Punto de Referencia
N#1	Núcleo 1	947209.7	258947.1	1.5 m	Entrada principal de aporte de agua de escorrentía
N#2	Núcleo 2	947155.3	258915.7	3.0 m	Más próximo al centro de la Laguna
N#3	Núcleo 3	947129.4	258893.2	1.5 m	Única salida de Agua

Figure 6. Sediment Core Sampling Points of La Rosa Lagoon

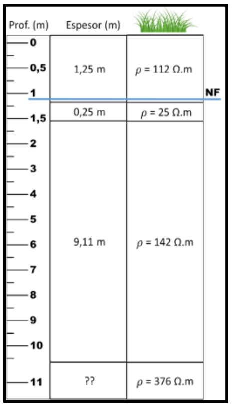
4 Results and Discussions

This section presents the results derived from the integration of geological, geophysical, geochemical, and isotopic information obtained in previous stages.

First, the geophysical results from the vertical electrical soundings (VES) are presented, which allowed obtaining 1D models with resistivities for 4–5 differentiated layers, revealing the presence of well-contrasted geoelectric units, from shallow levels of low resistivity associated with saturated fine materials to deeper strata of higher resistivity. Additionally, two phreatic levels were identified in the Mérida terrace: one shallow (1.25–11 m) and one deep (>40 m), both with variable resistivities (8–395 Ω·m) reflecting a heterogeneous stratigraphy composed of clays, silts, sands, and gravels. This configuration confirms that basement fractures act as preferential pathways for thermal water circulation, connecting superficial recharge (Albarregas River and streams) with discharge points located at the foot of the slope (Figures 7 and 8).

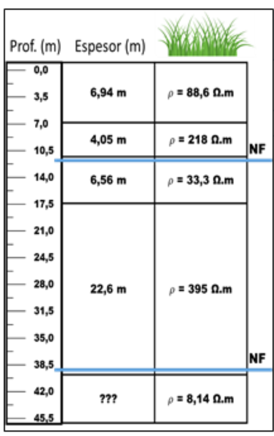
Regarding La Rosa lagoon, the processing of 347 georeferenced bathymetric points allowed constructing a detailed model of its internal morphometry. The contour lines show an asymmetric basin, with a deeper northwest sector and shallow marginal zones delineating an elongated contour, which evidences variable sediment thicknesses and an axis of maximum depth aligned with the fault trace (Figure 9). The morphometric parameters derived from this model indicate a surface area of 10,367 m², an estimated volume of

13,319 m³, and a maximum depth of 3.55 m in the northwest sector, where active tectonic subsidence is observed (current depths of 3–4 m compared to 1.5 m historically). The shoreline development index (DL = 1.45) and the length/width ratio (3.52) confirm an elongated triangular morphology, characteristic of a fault sag pond structurally controlled by the Boconó Fault.



Resistividad (Ωm)	Espesor (m)	Profundidad (m)	Tipo de Curva
112	1.25	1.25	HA
25	0.236	1.49	
142	9.11	10.6	
376	Indefinido	> 10.6	

Figure 7. Vertical Electrical Sounding No. 1 (UTM coordinates E258817.44 and N947250.52).



Resistividad (Ωm)	Espesor (m)	Profundidad (m)	Tipo de Curva
88.6	6.94	6.94	KHK
218	4.05	11	
33.3	6.56	17.5	
395	22.6	40.1	
8.14	Indefinido	>40.1	

Figure 8. Vertical Electrical Sounding No. 2 (UTM coordinates E260370.94 and N948270.73).

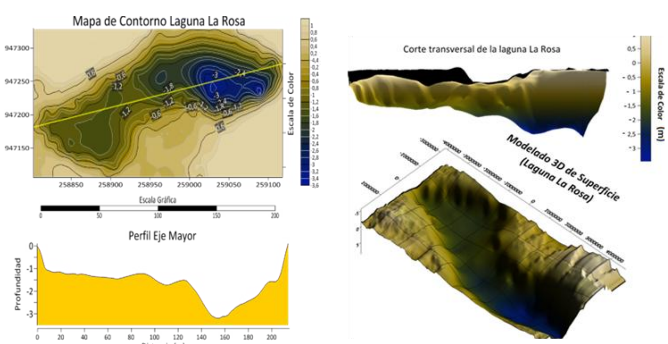


Figure 9. Morphometry and summary of the morphometric parameters studied in La Rosa lagoon.

From the cores it was possible to obtain that in core #1 (10a), taken near the main inflow of runoff waters into La Rosa lagoon, it is observed that sediment supply from the basin exceeds lacustrine redistribution, with clayey intervals rich in organic matter in the middle part that would correspond to periods of lower flow and dominance of proper lagoon sedimentation, and a prograding grain-size selection at the top from medium sands to fine gravels. Core #2, extracted at the edge of the wetland over an area previously occupied by the lagoon, reflects a filled environment with abundant soil and organic matter associated with the rooting of aquatic and semi-aquatic vegetation, reducing the water surface area, and shows at its base the beginning of the fine sediment bed. Core #3, located near the water outlet of the lagoon, presents various sedimentary structures that indicate changes in the depositional regime and, at the base, a possible biogenic structure or fluid escape that could be related to the seismicity of the area.

The physicochemical and isotopic analyses of 14 samples discriminate between the hydrogeological processes of the system. The thermomineral waters of El Chama and El Chamita present temperatures of 26.8–43.5 °C, elevated conductivities (up to 793 µS/cm), hardness of 172–397 mg $CaCO_3$/L, and ionic composition dominated by Ca^{2+}, Cl^-, and SO_4^{2-}, classifying as sodium-sulfated (Na–Ca–SO_4–HCO_3).

Their enriched $\delta^{18}O$ and δ^2H signatures, together with positive $\delta^{18}O$-Cl^- correlation, indicate deep circulation and progressive mineralization towards the NE.

Surface waters (Albarregas River, streams, runoff) align with the Local Meteoric Line, showing low conductivity and very soft hardness.

La Rosa lagoon exhibits isotopic displacement towards more positive values (intense evaporation) and diluted composition. Municipal network water occupies an intermediate position.

This suggests an affinity that can be summarized as follows: Affinity 1 ($\delta^{18}O$ < -8.5 ‰): Albarregas River, "Árbol" stream, La Rosa lagoon (center/outlet). Recharge from high sectors with dominant meteoric influence. Affinity 2 ($\delta^{18}O$ > -7.5 ‰): Runoff inflows to lagoon, El Chamita springs, Candelaria/Salomón thermal springs (El Chama). Underground flows with superficial evaporation and local recharge. Affinity 3: Municipal network water. No relation with thermal systems or lagoons.

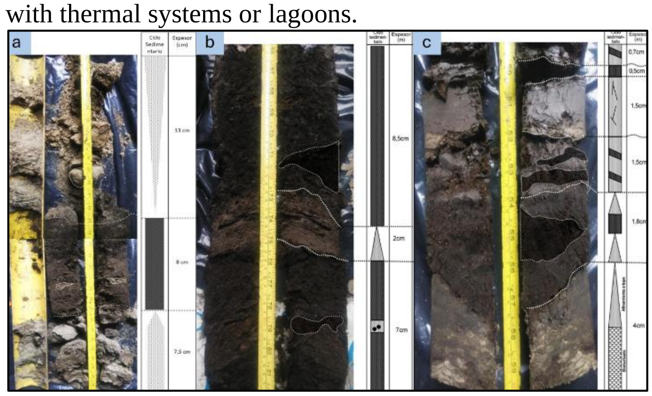


Figure 10. Image of extracted cores: a) #1, b) #2, and c) #3

All samples plot on the Global Meteoric Water Line ($\delta^{18}O$: -7.30 to -10.08 ‰; δ^2H: -46.57 to -63.75 ‰), confirming a primary meteoric origin. The decrease in Ca^{2+}, Mg^{2+}, Cl^{-}, and temperature compared to historical data supports meteoric recharge through fractures into deep circulation.

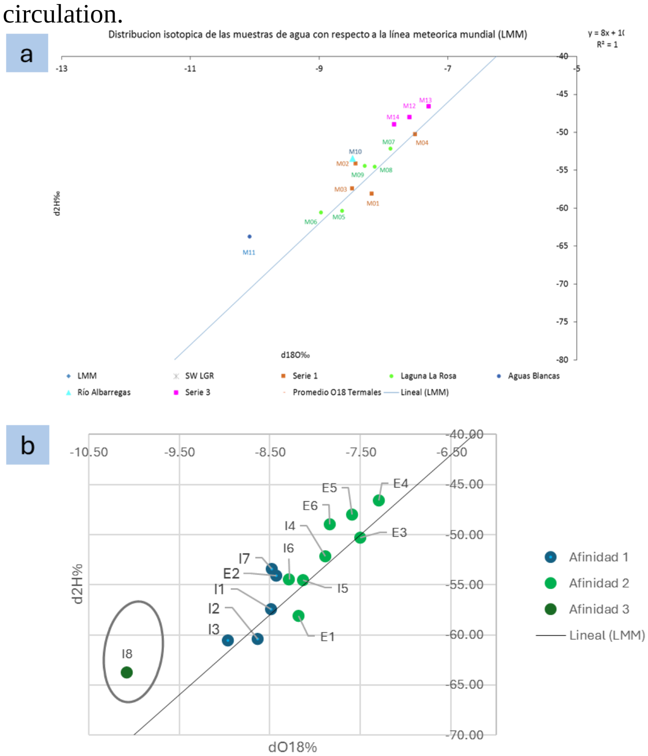


Figure 11. a. Isotopic Results. Sample names correspond to the ID in the tables. b. Chemical affinities plotted on the isotopic concentration graph.

The unification of geophysical and isotopic results allowed clarifying the hydrological connections of the thermal system of the Mérida terrace (Figure 12a). The VES faced urban limitations in Mérida, requiring cleared areas of 200 linear meters. VES-2 (Las Tapias, AB/2 = 100 m) identified two phreatic levels: one superficial at 11 m (thickness 6.56 m) and one deep at 40.1 m (undefined thickness) (Figure 12b). VES-1 (Av. Andrés Bello) detected a superficial aquifer at 1.25 m, consistent with the proximity of La Rosa wetland, suggesting favorable conditions for recharge of lower levels (Figure 13).

Isotopic integration evidence that contributions to La Rosa lagoon (I4, I5, I6) share geochemical affinity with outflows from El Chamita (E4, E5, E6) and low thermal springs of El Chama (E1, E3), explained by runoff channels, post-rainfall infiltration, and isotopic homogenization at the end of the rainy season. The Albarregas River maintains affinity with the "Árbol" thermal spring (higher altitude), indicating infiltration in terrace sediments that recharges deep aquifers emerging as thermal waters at the foot of the slope.

The unnamed stream (I1) also potentially feeds the "Árbol" and "Salomón" points (E1), confirming interaction between superficial and thermal systems through fractures and alluvial sediments of the terrace.

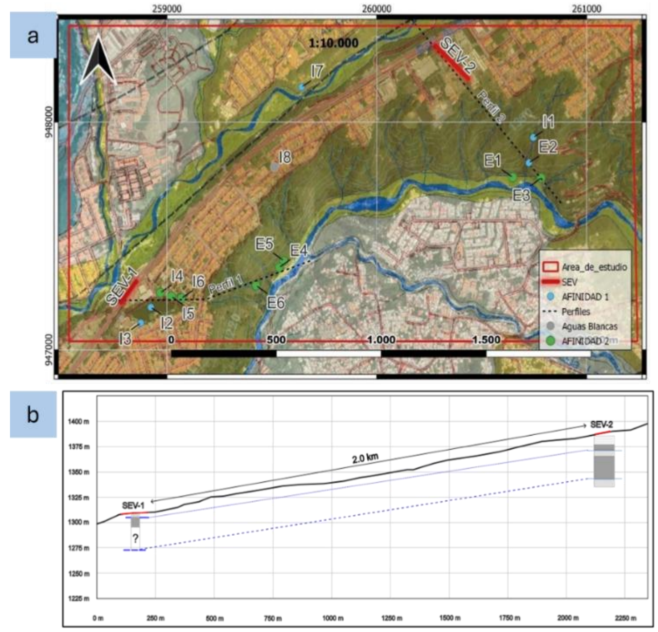


Figure 12. **a.** Location results of the affinities. **b.** Correlation of geophysical data on the elevation profile of the Mérida terrace.

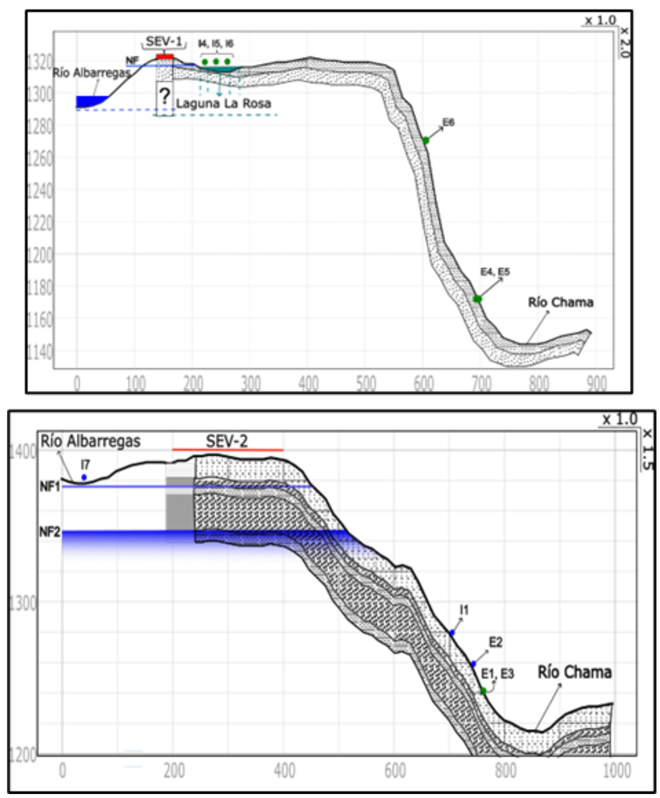


Figure 13. Profiles from VES-1 and VES-2 towards the discharge points in El Chamita.

5 Conclusion

The thermomineral waters of the Mérida terrace are of meteoric origin, infiltrate through basement fractures (controlled by the Boconó Fault), are heated by the geothermal gradient, and emerge at the foot of the slope with temperatures of up to 43.5 °C. Recharge comes from the Albarregas River, streams, and La Rosa lagoon, forming an active hydrothermal system linked to regional neotectonics.

The Boconó fault trace generates differential subsidence in the northwest of La Rosa lagoon, confirming its nature as a fault sag pond. The VES and bathymetry evidence variable sediment thicknesses and multiple phreatic levels, validating the active fault model in the Las Tapias-El Carrizal sector.

El Chama Sector (NE): waters are hyperthermal (41–43 °C), of high mineralization (SO_4-Na-Ca), and greater circulation depth.

El Chamita Sector (SW): waters are hypothermal (27 °C), of low mineralization, mixed with shallow waters, shorter ascending path or different fractures. Active landslides in El Chamita are hydrogeologically controlled by the emergence of thermal waters, which increases geomorphological risk. Water-rock interaction and the presence of deep CO_2 (inferred from high alkalinity) weaken the slope, accelerating mass removal processes.

The integration of hydrogeochemistry, stable isotopes, geophysics (VES), and bathymetry allowed delimiting recharge zones, mapping active faults, and characterizing thermal reservoirs, laying the groundwork for seismic risk studies and water resource management in the Metropolitan Area of Mérida.

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